Information about the images

Many instruments for gamma-ray astronomy, including those onboard ESA's INTEGRAL space observatory, rely on a technique called coded-mask imaging. A coded-mask camera is like a pinhole camera with more than one hole. It consists of a mask - with a special pattern of holes and opaque spots - that is placed in front of and about 3 meters away from a detector. The mask is designed with a particular pattern that was selected following detailed study of the properties of various patterns. Gamma rays pass through the holes and, depending on which direction they come from, cast a series of shadows on the detector corresponding to the positions of the opaque spots on the mask.

The pattern of shadows imprinted on the detector, contains information about the location of the source in the sky and its brightness. The intensity of the source of light determines the number of photons that are detected on the surface of the detector. The pattern of the mask is known, therefore, using both the intensity and shape of the shadow it is possible to reconstruct how bright the source is and where it is in the sky. When several sources are in the field of view, the processing software repeats the same procedures iteratively until all sources contributing to the photons reaching the detector have been taken into account

Making mosaics

An observation of a region of the gamma-ray sky in a given direction, or a pointing, lasts between 30 and 60 minutes, and yields a single image, an individual snapshot. During one observation, very few photons are detected from any given source. Therefore it is necessary to make a number of observations in the same direction of the sky in order to actually see something. It is like taking a picture at night in low lighting conditions. The shutter needs to be open for a long time to allow as much light as possible to come into the camera and eventually trace the shape of the objects present in the field of view. Making a mosaic, like the ones provided for the *Explore the high-energy Universe* competition research project, is done by combining a number of individual images. This enables objects that appear faint in an individual snapshot to be seen more clearly.

Energy bands

To make images in 3 different energy bands, all the photons whose energy was measured to be between 20 and 35 keV, for example, are combined to make a mosaic image in this energy range. The same is done for the range between 35 and 65 keV, and for the range between 65 and 100 keV. These give three different mosaics of the same portion of the sky, that therefore contain the same sources.

Intensity images

An intensity image shows how many photons per second are detected from each source. The best estimate of this intensity is the value in the very centre of the source. Each source is spread across many pixels, typically 3x3 or 4x4 pixels. This is because these images are a reconstruction of what the sky looks like taken from a mask shadow and are not perfectly accurate; it is statistically the most probable reconstruction given the data available.

Variance images

Note: these images are not needed for the main research project of the *Explore the high-energy Universe* competition, but are made available as a possible extension for older students.

A variance image is basically the inverse of the number of photons detected from a given direction in the sky. Since both the mask and the detector are square in shape, and no light can reach the detector without going through the mask, the centre of the detector gets the most light, and the edges get the least. Therefore, the general shape of the variance image is that of an upside down, square-based pyramid (like a bowl with a flat, square-shaped bottom and square sides that rise-up steeply at the edges). The more photons that are detected during an observation, the flatter the centre and the smoother the entire variance image will be. Hence, the variance image is used to provide information about the accuracy of the estimates made for the intensity of a source in the accompanying intensity image.

Significance images

Note: these images are not needed for the main research project of the *Explore the high-energy Universe* competition, but are made available as a possible extension for older students.

A significance image is the intensity image divided by the square root of the variance image. This is an image of the signal-to-noise ratio. It is a weighted intensity image in which each value of the intensity is scaled inversely with the variance: the lower the variance, the higher the significance. This is a way to incorporate a quantitative measure of our confidence about the intensity estimates based on the information available both in the intensity image and in the variance image.

Pseudo-RGB images

The colourful pseudo-RGB images are made by combining the significance images of the three different energy bands. Each of the three energy bands are associated with one of the colours: red, green, blue. Some sources emit more of their light at lower energies, some at middle energies, some at higher energies, some equally across all energies, and this results in different colours in the pseudo-RGB images. For example, if a source is only seen to emit up to 35 keV, then this source will be completely red in these images because it is not visible in the other two energy ranges. If, on the other hand, a source is only seen in the highest energy band between 65 and 100 keV, then it will appear to be completely blue.

There are some corrections that need to be made. As in any colour device, such as your own digital camera, we need to calibrate the colours, and in this case, define what 'white' is. As you might expect, all sources emit more at lower energies than they do at higher energies. What changes from one source to another is how much more. Therefore, we need to use a reference emission spectrum, and identify this as 'white'. The standard reference spectrum in high-energy astrophysics is that of the Crab Nebula and it is a power-law with an index of -2. This is what has been used to create the pseudo-RGB images for the competition and means that a source will be white when the number of photons decreases like a power-law with index -2 as the energy increases.

Next, the scale to be used to display each different energy band needs to be defined. For a power-law with index -2, the way that the number of photons decreases is as follows: If there were 100 photons detected in the 20-35 keV band, there would be 40 in the 35-65 keV band, and 20 in the 65-100 keV band.

In order to ensure that each band contributes equally to the intensity of the colours, each one is scaled according to their relative contribution. This is done by defining what should be considered the minimum and maximum values in each image. The image display scale is set from 5 to 100 for the first energy band because anything below 5 is not considered significant and the brightest sources have a signal-to-noise around 100. In the middle energy band, the range of significance values is smaller, and therefore an appropriate scale must be used so that the sources appear as bright as sources in the first band. So, for the middle band a scale of 6 to 40 is used and a scale of 8 to 20 is used for the highest energy band (there is more noise in the highest band, and so only detections above a signal-to-noise ratio of 8 are considered. This will yield white sources when these have an index -2 power-law spectrum.